U.S. DEPARTMENT OF ENERGY | Office of Science

Nuclear Physics: Present Status and Future Challenges

RHIC/AGS User Meeting
June 8, 2010

Office of Nuclear Physics
Exploring Nuclear Matter - Quarks to Stars

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Nuclear Physics Program Mission

Mission: To discover, explore and understand all forms of nuclear matter; to understand how the fundamental particles, quarks and gluons, fit together and interact to create different types of matter in the universe, including those no longer found naturally

Priorities:

- To understand how quarks and gluons assemble into the various forms of matter and to search for yet undiscovered forms of matter
- To understand how protons and neutrons combine to form atomic nuclei and how these nuclei have emerged during the 13.7 billion years since the origin of the cosmos
- To understand the fundamental properties of the neutron and develop a better understanding of the neutrino
- To conceive, plan, design, construct, and operate national scientific user facilities; to develop new detector and accelerator technologies
- To provide stewardship of isotope production and technologies to advance important applications, research and tools for the nation
- To foster integration of the research with the work of other organizations in DOE

The Focus of the Present Program

- The Quark Structure of the Nucleon and Nuclei
  - What is quark-gluon structure of the nucleon and how is it manifest in neutrons and protons in nuclei?
- Quark-Gluon Matter
  - What are the fundamental properties of a quark-gluon liquid? How do the properties change at higher energy?
- Nuclei Near the Limits of Stability
  - What is the structure of nuclei; what nuclei exist near the limit of stability; does an island of stability exist for the heaviest nuclei; how are elements synthesized in the universe; what processes drive stellar supernovae ?
- Weak Interaction and Fundamental Studies
  - What are the fundamental properties of the neutrino and what role do neutrinos play in cosmological processes?
- Cold and Ultra-cold Neutrons
  - What are the fundamental properties of the neutron?
  - Are there observable low-energy manifestations of physics beyond the Standard Model?
- Nuclear Theory
  - What new knowledge derives from observation and concept ; what intellectual bridges do these provide to other scientific fields
- Isotopes
  - How can isotopes serve society in new ways; how can production be improved?
- Applications of Nuclear Science and Technology and R&D Integration
  - How can knowledge gained and core competency in nuclear science serve society and national priorities?

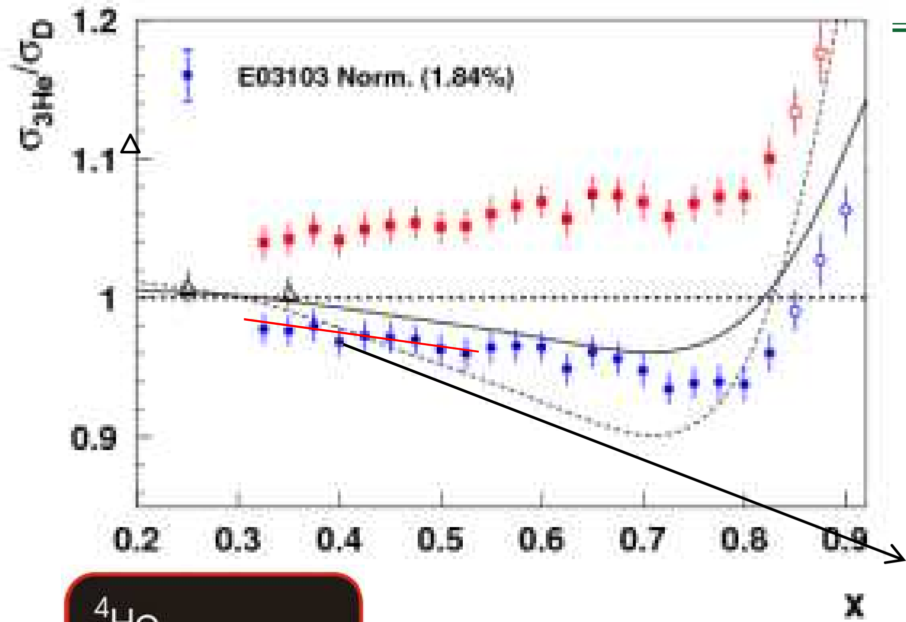
Overview of the Near-Term Investment Strategy by Sub-Field

Nuclear Physics FY 2011 Congressional Request

	FY 2009 Approp.	FY2009 ARRA	FY 2010 Approp.	FY 2011 Request	FY11 Request vs. FY10 Approp. $	FY11 Request vs. FY10 Approp. %
Medium Energy Nuclear Physics	116,873	+15,390	127,590	129,610	+2,020	+1.6%
Heavy Ion Nuclear Physics	194,957	+12,669	212,000	218,435	+6,435	+3.0%
Low Energy Nuclear Physics	94,880	+29,667	114,636	113,466	-1,170	-1.0%
Nuclear Theory	37,776	+17,237	41,574	44,709	+3,135	+7.5%
Isotope Program	24,760	+14,837	19,200	19,780	+580	+3.0%
Subtotal, Nuclear Physics	469,246	+89,800	515,000	526,000	+11,000	+2.1%
Construction	31,061	+65,000	20,000	36,000	+16,000	+80.0%
Total, Nuclear Physics *	**500,307**	**+154,800**	**535,000**	**562,000**	**+27,000**	**+5.0%**

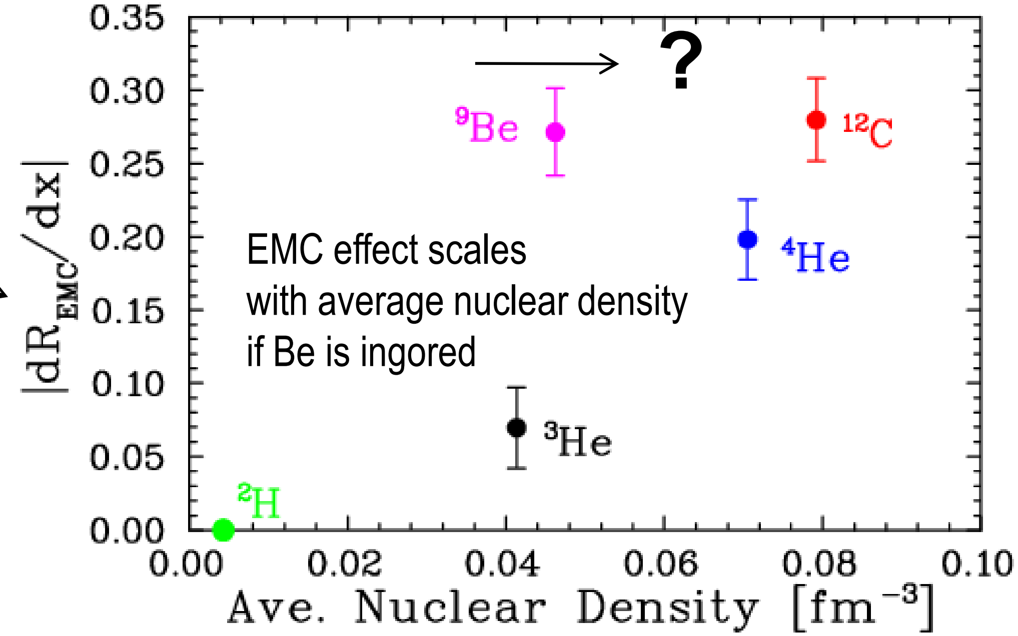
* SBIR/STTR for FY 2009 was $11,773k. Comparable NP total w/SBIR/STTR in FY 2009 is $512,080k.

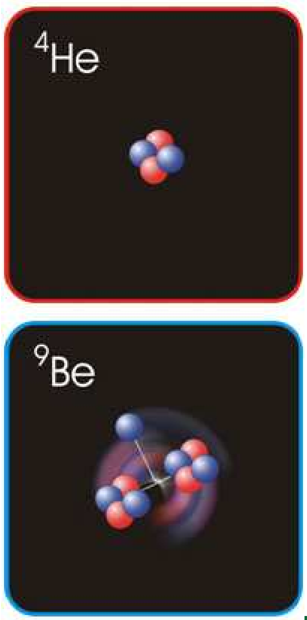
The Quark-Gluon Structure of Nuclei



EMC Effect in Very Light Nuclei at TJNAF

EMC effect scales with average nuclear density if we ignore Be





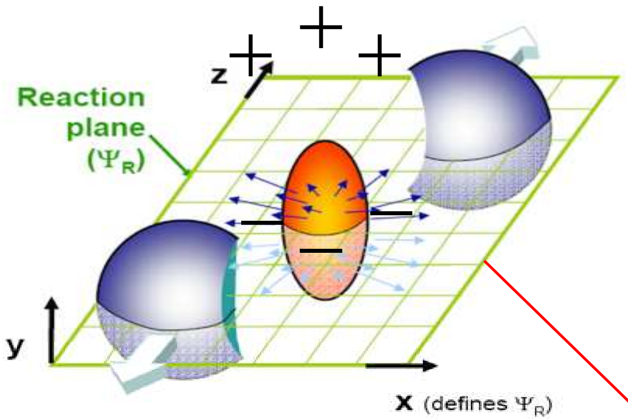
Be = 2 α clusters (^{4}He nuclei) + "extra" neutron. Suggests EMC effect depends on ***local*** nuclear environment

dR/dx = slope of line fit to A/D ratio over region x=0.3 to 0.7

Nuclear density extracted from ab initio GFMC calculation – scaled by (A-1)/A to remove contribution to density from "struck" nucleon

Fundamental Properties of a Quark-Gluon Liquid

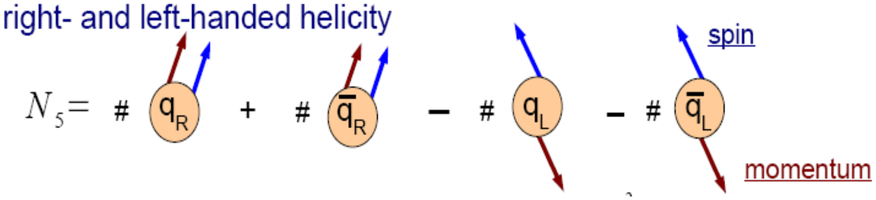
Magnetic field generated by motion of ions

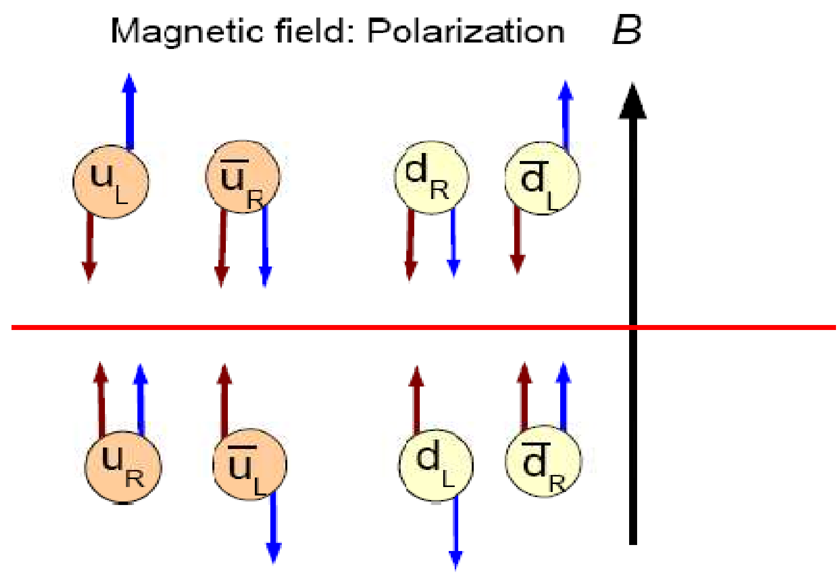


Event-by-event preference for like-sign (opposite-sign) charges to emerge in same (opposite) direction with respect to magnetic field produced by colliding nuclei observed

Topological charge induces chirality

Chirality: difference between number of quarks + antiquarks with right- and left-handed helicity

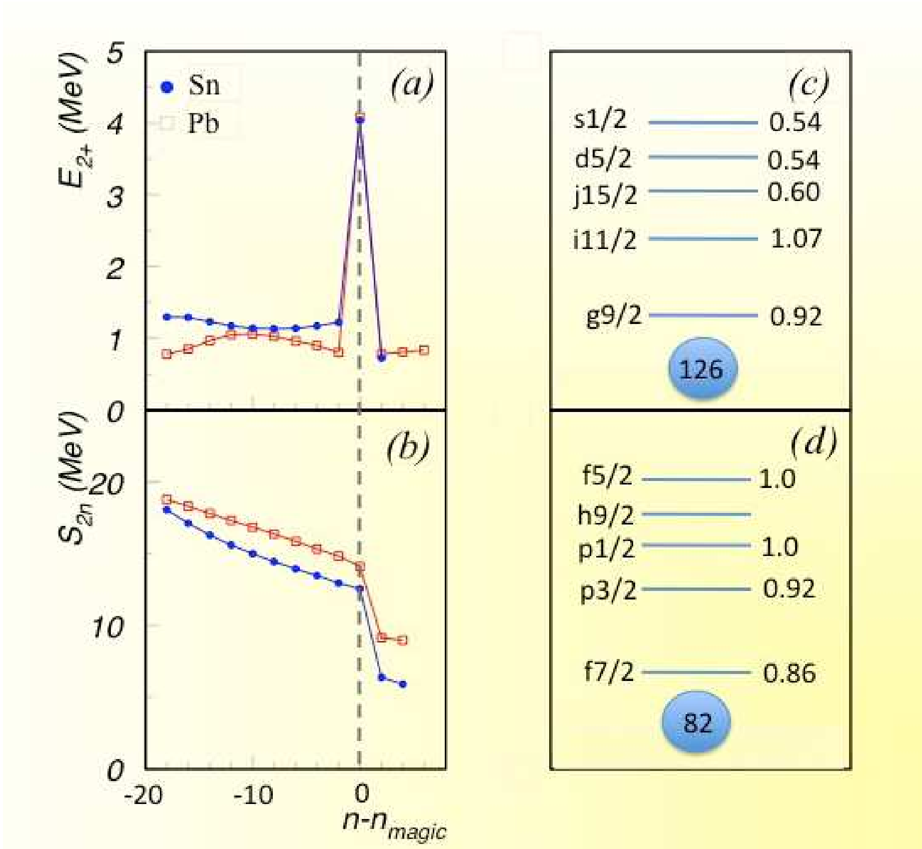




Spin of quarks aligns along the magnetic field

Right and left handed quarks move in opposite directions

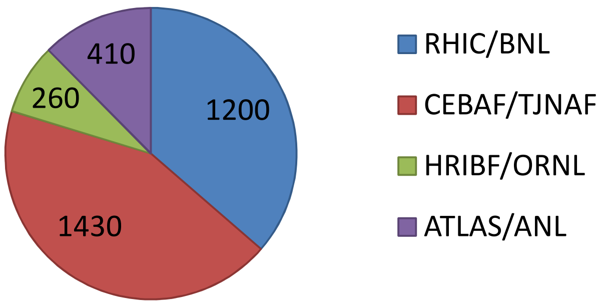
Structure of Nuclei

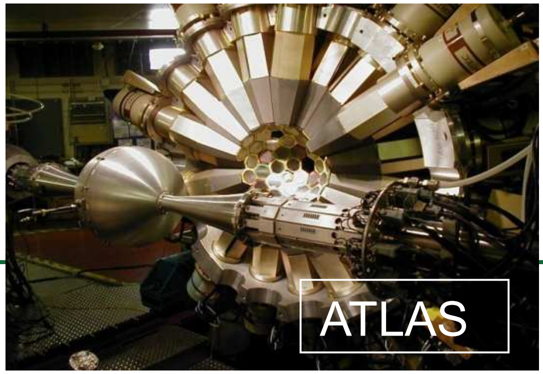


Observation of a new single particle state ^{133}Sn created by from a single neutron transfer reaction on doubly magic ^{132} Sn ($T_{1/2}$ = 39.7 s) at an excitation energy of 1363 KeV provides a new "laboratory" to test nuclear models used to extrapolate to exotic nuclei out of the range of current experiments

A Major Program Component: Providing Quality Nuclear Beams for the Research Community

Users of NP Facilities





- Four National User Facilities
- Approximately 40% of users are from foreign institutions
- FRIB, when complete, will also be a National User Facility

Near term strategic directions based on 2007 NSAC Long Range Plan

Recommendations:

- We recommend completion of the 12 GeV CEBAF Upgrade at Jefferson Lab. The Upgrade will enable new insights into the structure of the nucleon, the transition between the hadronic and quark/gluon descriptions of nuclei, and the nature of confinement.
  - **Construction underway**
- We recommend construction of the Facility for Rare Isotope Beams (FRIB), a world-leading facility for the study of nuclear structure, reactions, and astrophysics. Experiments with the new isotopes produced at FRIB will lead to a comprehensive description of nuclei, elucidate the origin of the elements in the cosmos, provide an understanding of matter in the crust of neutron stars, and establish the scientific foundation for innovative applications of nuclear science to society.
  - **CD-1 review planned for this year**
- We recommend a targeted program of experiments to investigate neutrino properties and fundamental symmetries. These experiments aim to discover the nature of the neutrino, yet-unseen violations of time-reversal symmetry, and other key ingredients of the New Standard Model of fundamental interactions. Construction of a Deep Underground Science and Engineering Laboratory is vital to U.S. leadership in core aspects of this initiative.
  - **Projects underway (KATRIN, CUORE, Majorana Demonstrator, FNPB, neutron EDM)**
- The experiments at the Relativistic Heavy Ion Collider have discovered a new state of matter at extreme temperature and density—a quark-gluon plasma that exhibits unexpected, almost perfect liquid dynamical behavior. We recommend implementation of the RHIC II luminosity upgrade, together with detector improvements, to determine the properties of this new state of matter.
  - **RHIC luminosity and detector upgrades in progress**

Additional NSAC Recommendations

We recommend the allocation of resources to develop accelerator and detector technology necessary to lay the foundation for a polarized Electron- Ion Collider. The EIC would explore the new QCD frontier of strong color fields in nuclei and precisely image the gluons in the proton. ✓

We recommend the funding of finite-duration, multi-institutional topical [theory] collaborations initiated through a competitive, peer-review process. ✓

Targeted support of proposal-driven accelerator Research and development supported by DOE and NSF nuclear physics. ✓

The construction of GRETA should begin upon successful completion of GRETINA. This gamma-ray energy tracking array will enable full exploitation of compelling science opportunities in nuclear structure, nuclear astrophysics, and weak interactions.

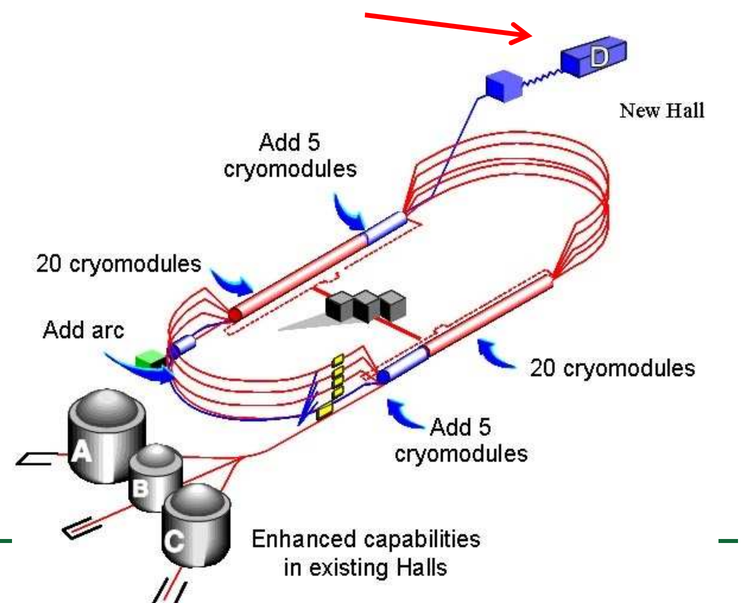
The enhancement of existing programs and the inception of new ones that address the goals of increasing the visibility of nuclear science in undergraduate education and the involvement of undergraduates in research; ✓

The development and dissemination of materials and hands-on activities that demonstrate core nuclear science principles to a broad array of audiences. ✓

Implementing the Recommendations of the Long Range Plan

New physics reach provided by the 12 GeV CEBAF Upgrade:

- Nuclear tomography to discover and explore the three-dimensional structure of the nucleon
- The search for exotic mesons—a quark and an anti-quark held together by gluons, but unlike conventional mesons, the gluons are excited
- Physics beyond the Standard Model via high precision studies of parity violation
- The spin and flavor dependence of valence parton distributions—the heart of the proton, where its quantum numbers are determined
- The structure of atomic nuclei, exploring how the valence quark structure is modified in a dense nuclear medium



Implementing the Recommendations of the Long Range Plan

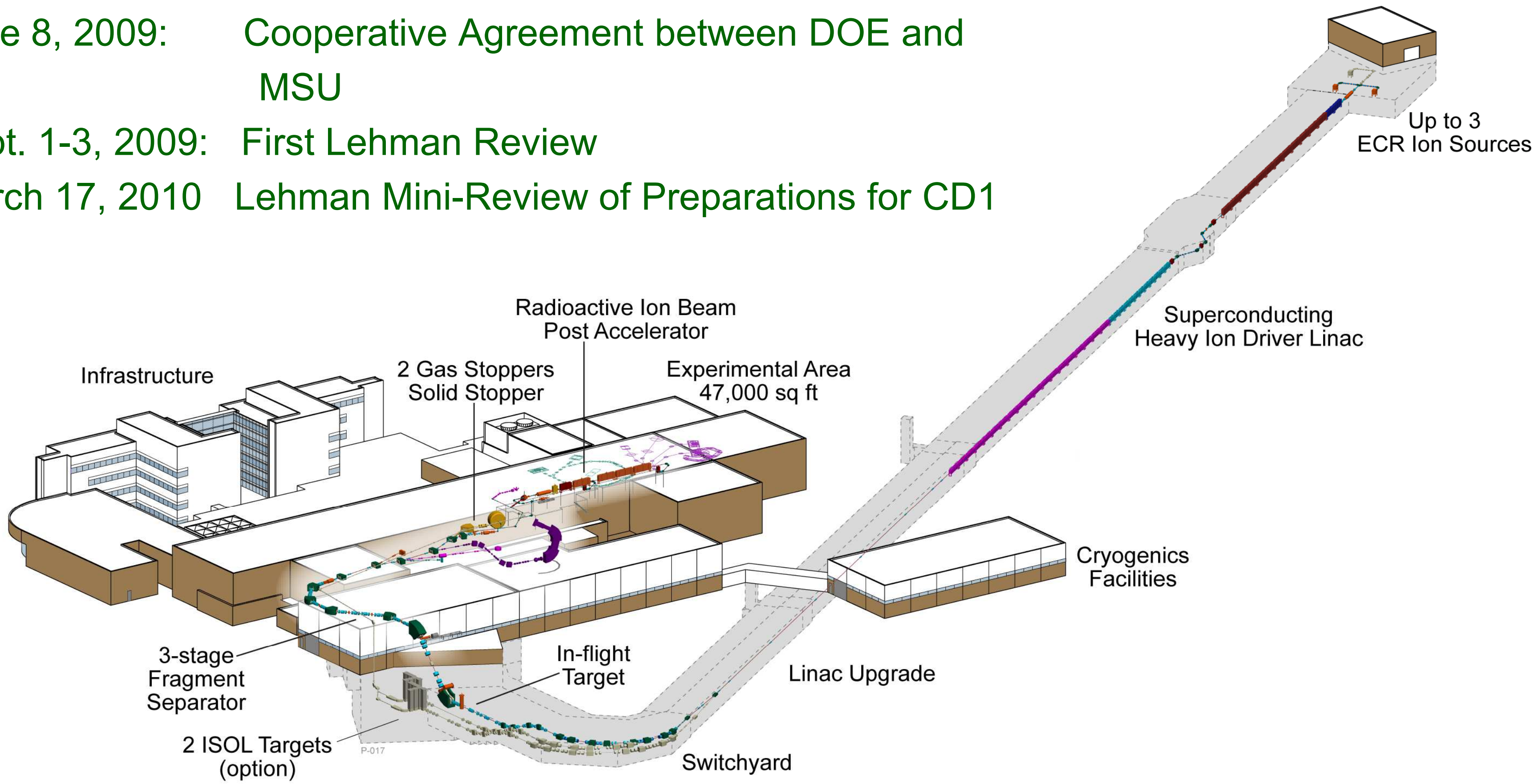
Dec. 11, 2008: DOE selects MSU to establish FRIB

May 7, 2009: Roll-out of NSCL/FRIB organization

June 8, 2009: Cooperative Agreement between DOE and MSU

Sept. 1-3, 2009: First Lehman Review

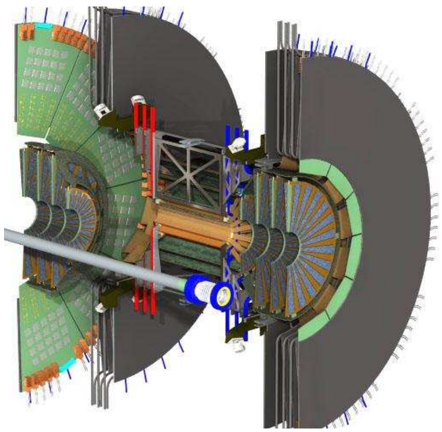
March 17, 2010 Lehman Mini-Review of Preparations for CD1



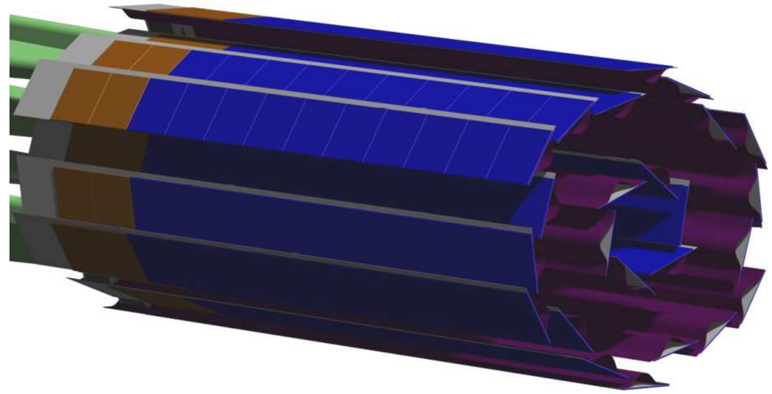
Expect to request the start of engineering design in FY 2011

Implementing the Recommendations of the Long Range Plan

Luminosity and detector upgrades are underway for RHIC

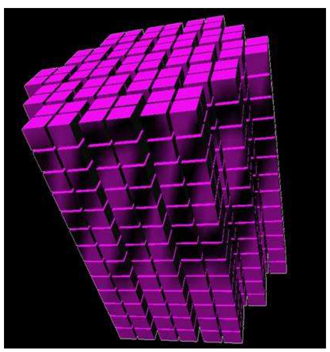


PHENIX Barrel and Forward Vertex Detector

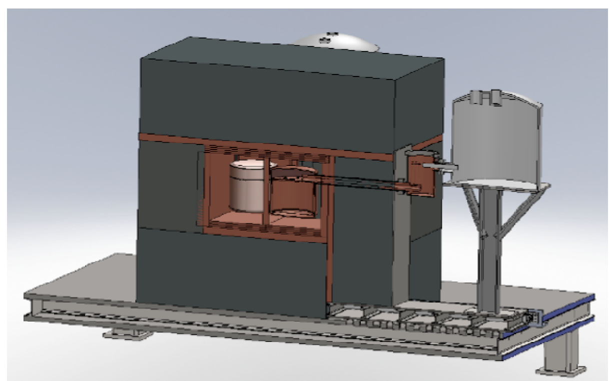


STAR Heavy Flavor Tracker

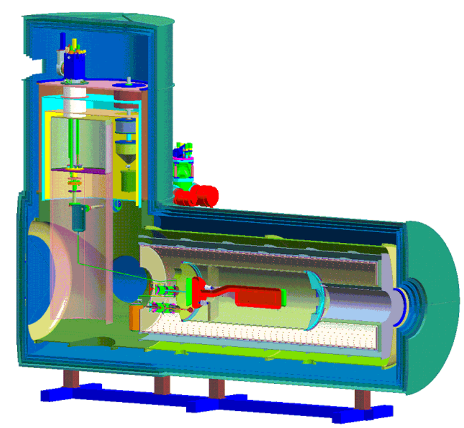
Investments in neutrons, neutrinos, and fundamental symmetries



CUORE receives CD2/3



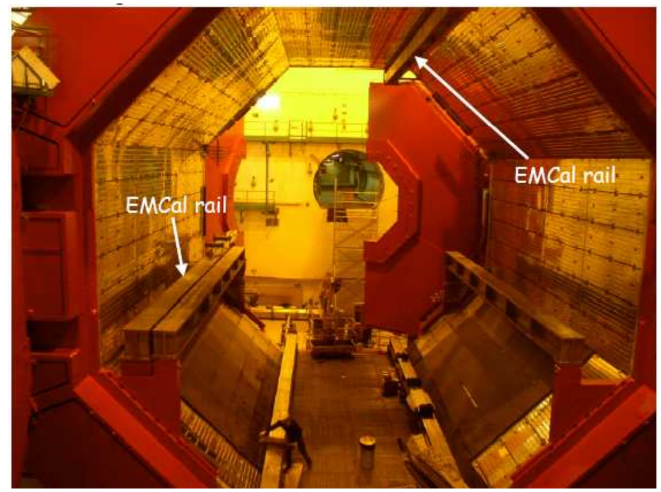
Majorana Demonstrator Underway



R&D for nEDM

Investment in Heavy Ion Physics at the Large Hadron Collider

EMCAL for the ALICE experiment
(DOE TPC = $13.5M) FY 2007-FY 2011



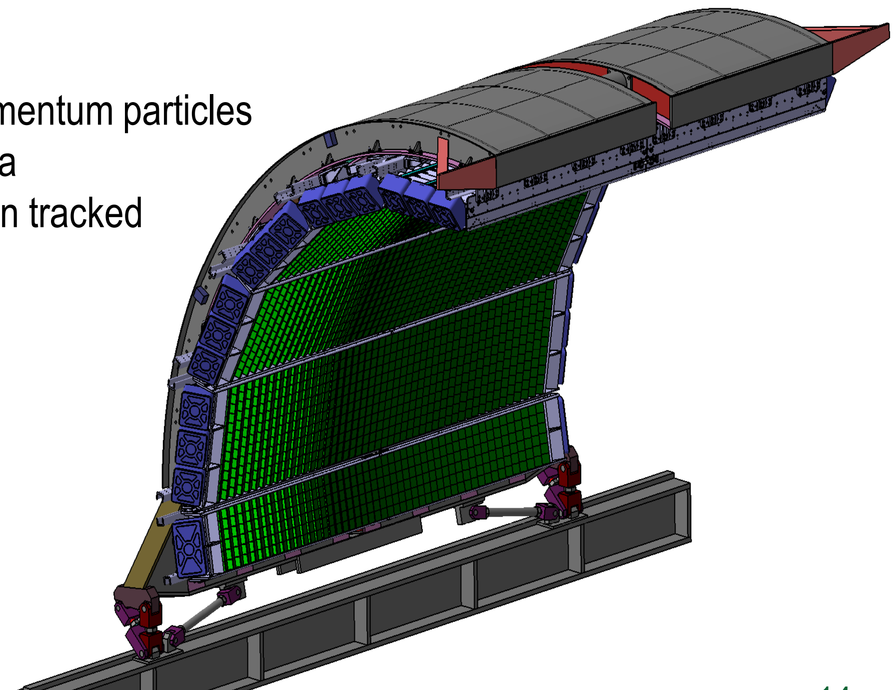
- LHC - world's highest energy facility for particle physics; heavy ion studies @ ~4 wks/yr
- Electromagnetic calorimeter (EMCal) for the ALICE experiment
- Joint U.S., French, and Italian project
- NSAC HI subpanel (2004) - LHC offers significant opportunities

Significant extension of the High Level Trigger for the CMS experiment: (DOE Investment = $1.2M)

- Significant extension of the reach for high transverse momentum particles
- Dramatic enhancement in yield and p_T reach for quarkonia
- Efficient tracking of low momentum particle in inner silicon tracked

Physics Agenda:

- Triggering on high p_T π_0, gammas and electrons to study jet quenching through leading particles
- Hard processes modified by the nuclear medium
- Jet correlations and jet reconstruction



Nuclear Physics Isotopes Program

Background:

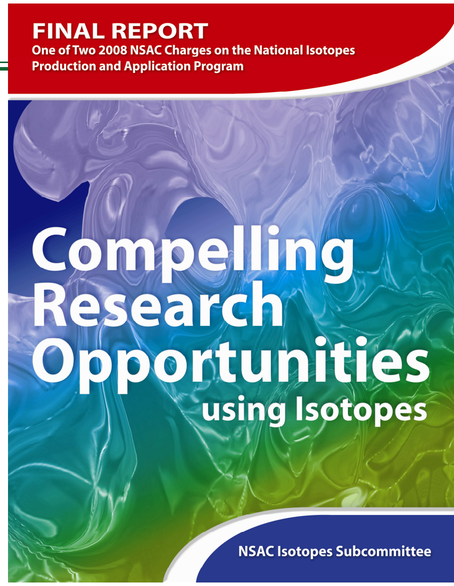
- Isotope Program was transferred to the Office of Nuclear Physics in the 2009 Appropriation. The program was renamed Isotope Development and Production for Research and Applications (IDPRA) and aligned more closely with the SC mission
- Research and development of isotope production techniques and the production of research isotopes was re-established

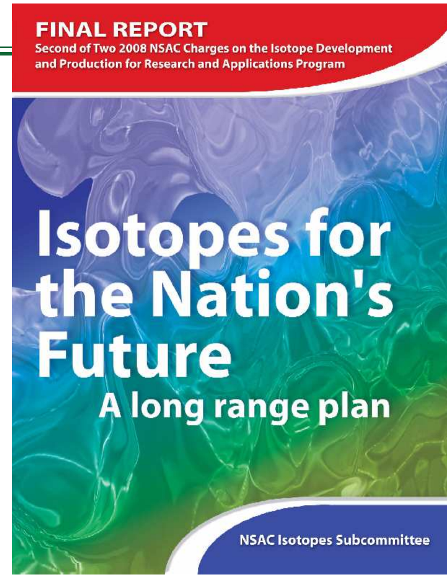
Team leaders for program transfer and reorganization:
Jehanne Gillo, John Pantaleo

Mission Definition:

- Produce and/or distribute radioactive and stable isotopes that are in short supply, associated byproducts, surplus materials and related isotope services.
- Maintain the infrastructure required to produce and supply isotope products and related services.
- Conduct R&D on new and improved isotope production and processing techniques which can make available new isotopes for research and applications.

A Strategic Plan Created by the Nuclear Science Community





Main recommendations on which work is ongoing (✓) or a plan is being developed…

- Maintain a continuous dialogue with all stakeholders to forecast and match realistic demand ✓
- Coordinate production capabilities and supporting research ✓
- Support a sustained research program …to enhance production and supply of isotopes ✓
- Better communication with stakeholders ✓
- Encourage the use of isotopes for research through reliable availability at affordable prices ✓
- Increase the robustness and agility of isotope transportation both nationally and internationally (in progress)
- Workforce development (✓)
- **Construct and operate an electromagnetic isotope separator facility for stable and long-lived radioactive isotopes** (plan in development)
- **Construct and operate a variable-energy, high-current, multi-particle accelerator and supporting facilities that have the primary mission of isotope production** (plan in development)

Production Sites Presently Integrated into the Isotope Program

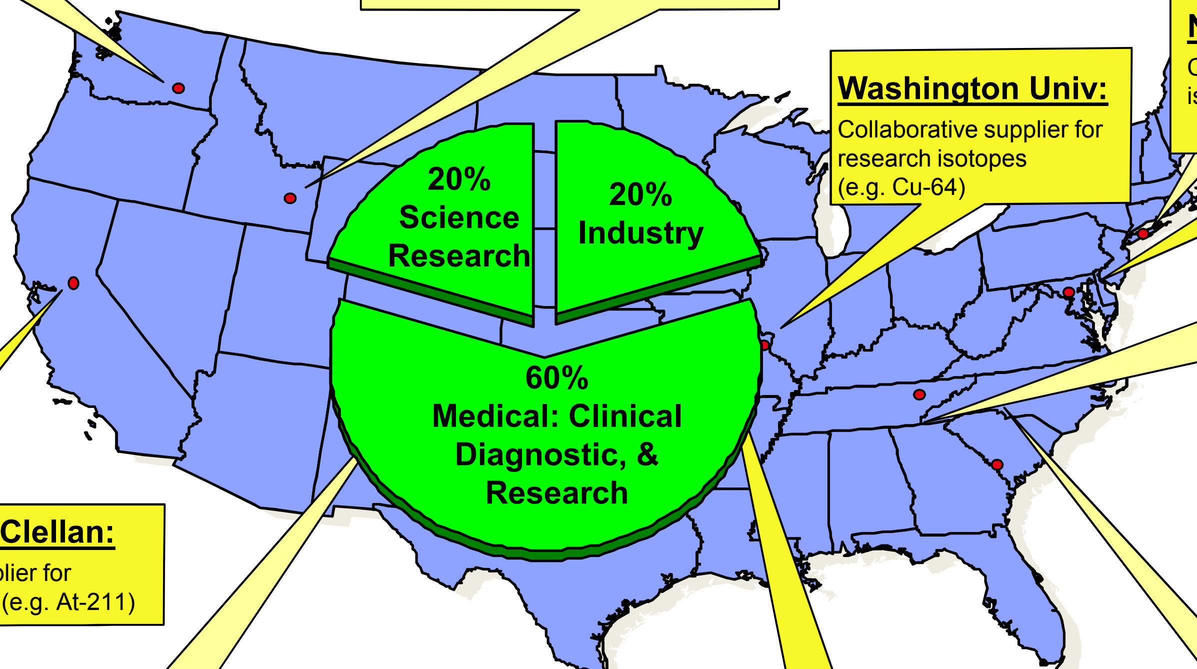
Richland:
Sr-90 – Y-90 gen for cancer therapy

Idaho – ATR:
Co-60 – Sterilization of surgical equipment and blood

Brookhaven – BLIP:
Ge-68 – Calibration sources for PET equipment; Antibody labeling
Sr-82 – Rb-82 gen used in cardiac imaging
Cu-67 – Antibody label for targeted cancer therapy

NIH - Cyclotrons:
Collaborative supplier for research isotopes (e.g. Br-76)

Washington Univ:
Collaborative supplier for research isotopes (e.g. Cu-64)



Oak Ridge – HFIR:
Se-75 - Industrial NDA; Protein studies
Cf-252 - Industrial source
W-188 - Cancer therapy

Stable Isotopes Inventory:
Top 10 stable isotopes sold over the last 5 years:
Ca-48, Ga-69, Rb-87, Cl-37, Pt-195, Nd-146, Sm-149, Ru-99, Zr-96

Inventory:
Ac-225 - Cancer therapy

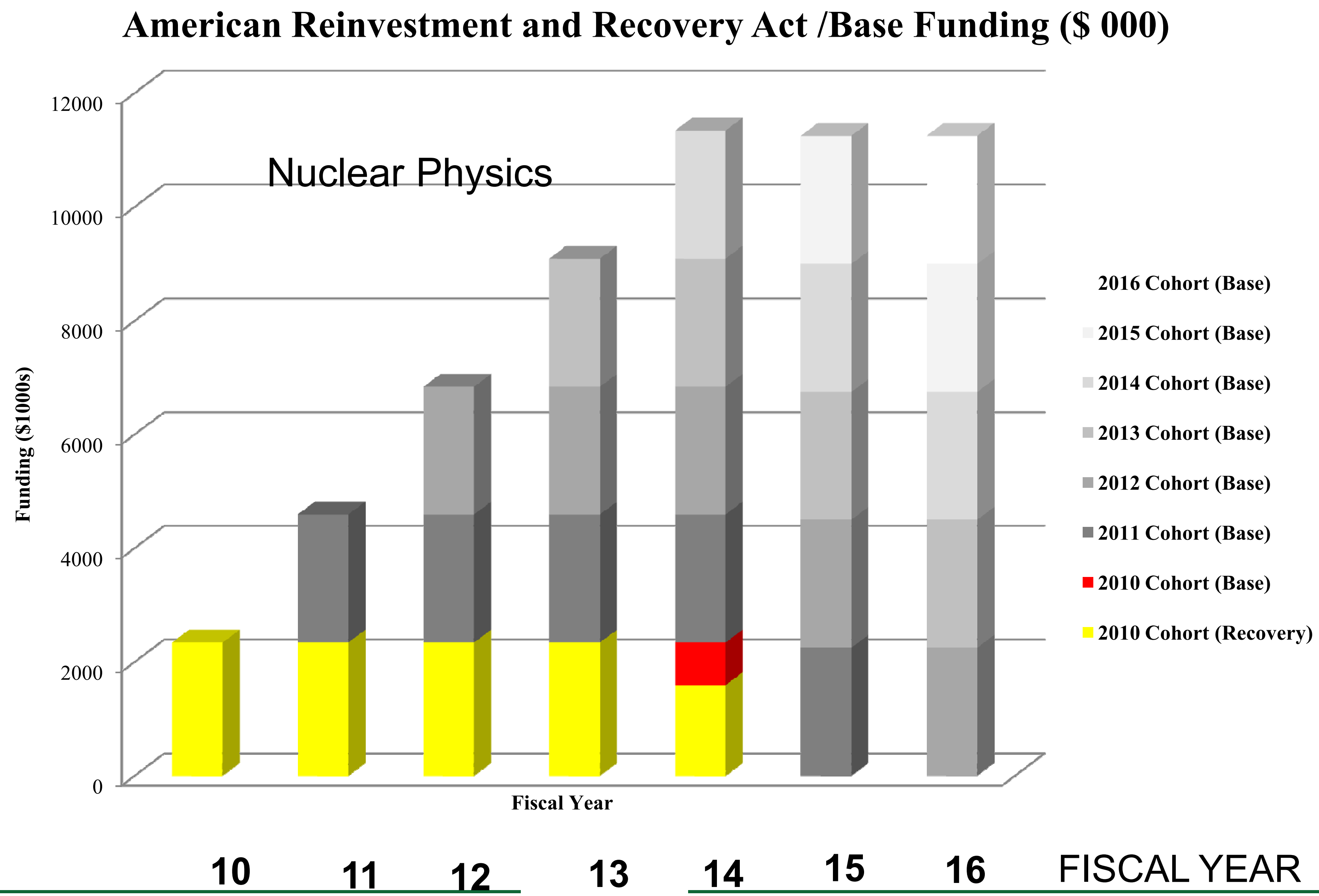
UC Davis/McClellan:
Collaborative supplier for research isotopes (e.g. At-211)

Columbia – MURR:
Collaborative supplier for research isotopes (e.g. As-72)

Los Alamos – LANSCE/IPF:
Ge-68 – Calibration sources for PET equipment; Antibody labeling
Sr-82 – Rb-82 gen used in cardiac imaging
As-73 – Biomedical tracer

Savannah River – Tritium Facility: (NNSA)
He-3 – Neutron detection
– Fuel source for fusion reactors
– Lung testing

Science Early Career Research Award Program Funding



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A continuing commitment to the ECRA Program is planned

Program news in Nuclear Theory

National Lab Theory Program Review Sept. 16-18 , 2009 Reports out Jan, 2010

Funding Opportunity Announcement for Topical Theory Collaborations

Selection announced Dec 14, 2009

"Jet and Electromagnetic Tomography (JET) in Heavy-Ion Collisions "
Principal Investigator/Project Director: X-N. Wang (LBNL), eight collaborating institutions

"Advancing the Theory of Nuclear Reactions with Rare Isotopes: From the Laboratory to the Cosmos "
Principal Investigator/Project Director: I. Thompson (LLNL), four collaborating institutions

"Neutrinos and Nucleosynthesis in Hot and Dense Matter"
Principal Investigator/Project Director: S. Reddy (LANL), six collaborating institutions

Topical Collaborations are fixed-term, multi-institution collaborations established to investigate a specific topic in nuclear physics of special interest to the community, which is well aligned with programmatic NP goals.

What needs does the basic research program drive (partial list)?

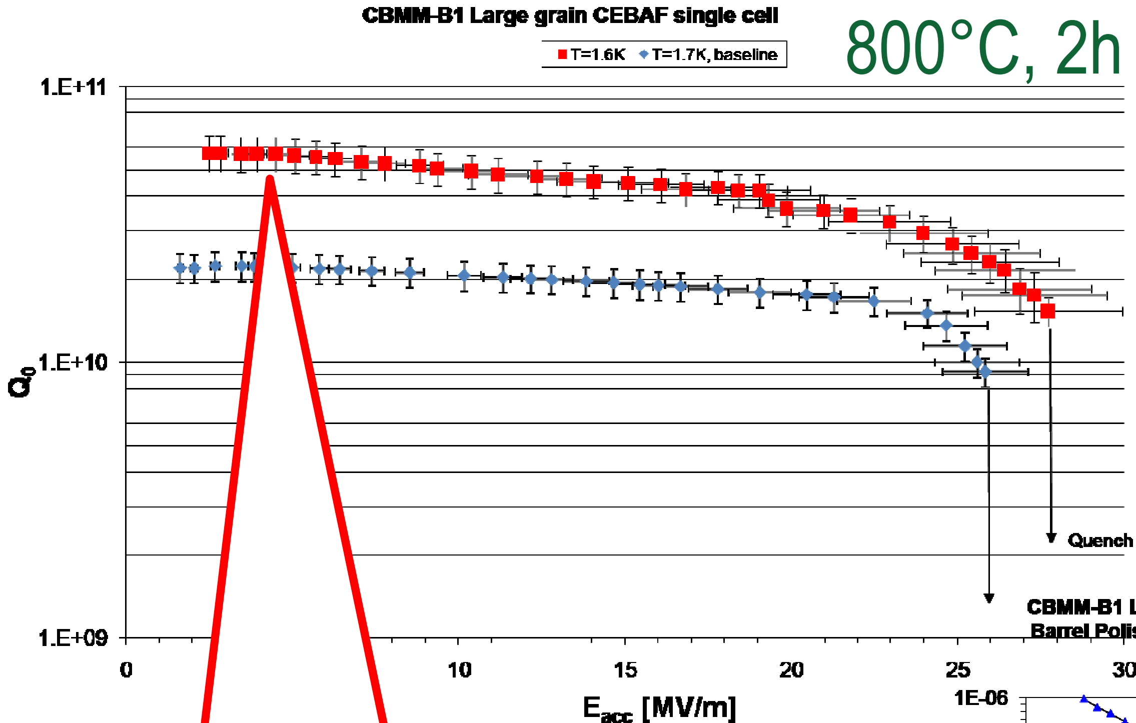
- Interaction of particles and matter; Need to efficiently detect and identify particles of all types, charged and neutral, often at the 1 ppb level
- Mass spectrometry
- Isotope production and separation (chemical and in-flight); half life
- Laser trapping
- High current ion production, plasma injection
- Beam transport, beam cooling
- Particle acceleration
- Superconducting RF
- Charge breeding
- Charge stripping
- Interaction of particles and matter
- High speed, high volume data logging, mining, and analysis
- Polarization of intrinsic spin
- Knowledge of reaction rates, capture cross sections, limits of nuclear stability
- High vacuum; high voltage; high power switching;

etc., etc., etc.…..

and the requirements of the science drive you to do it faster, more precise, more intense, cheaper, with less energy, more reliably, in a different way…than its ever been done before

And… pushing the technology envelope because of what you want or need to accomplish in basic research drives innovation in (often unexpected) ways that align with national priorities

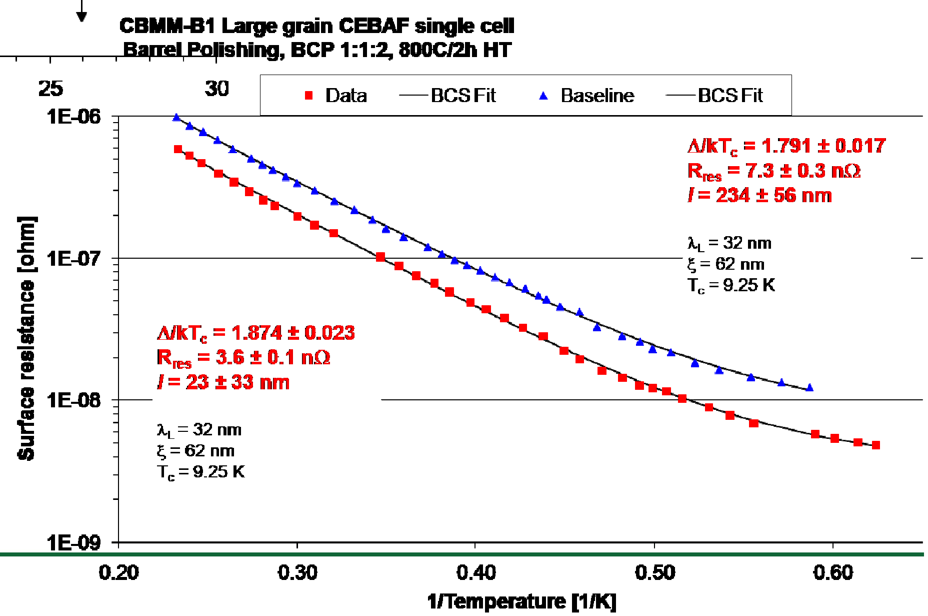
Case in point: Development of SRF Accelerating Structures in Nuclear Science



800°C, 2h Large grain CBMM"B1"

Uniformly smooth surface by barrel polishing

High Q Values
First results from DOE-NP ARRA-funded Program



Surface preparation and test by G. Ciovati

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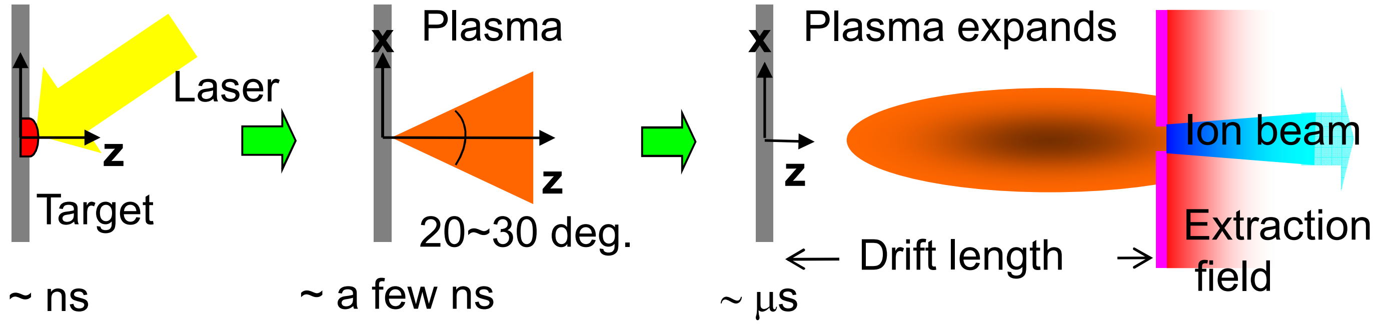
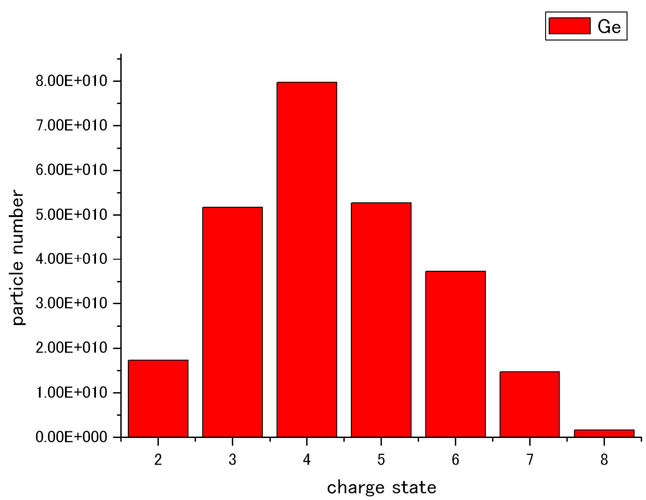
Long pulse laser ion source for heavy ion pre-injector (RHIC)

A laser ion source has been studied as a versatile method of producing low charge state ion beams as part of a new heavy ion pre-injector for RHIC. It is also useful to provide high current medium charge state ion beams.



A low power, commercially available laser is used to ablate and ionize material from solid targets, producing a plasma containing low charge state ions in a very simple system. This plasma drifts to a short electrostatic acceleration gap, to produce a beam of the desired ion species.



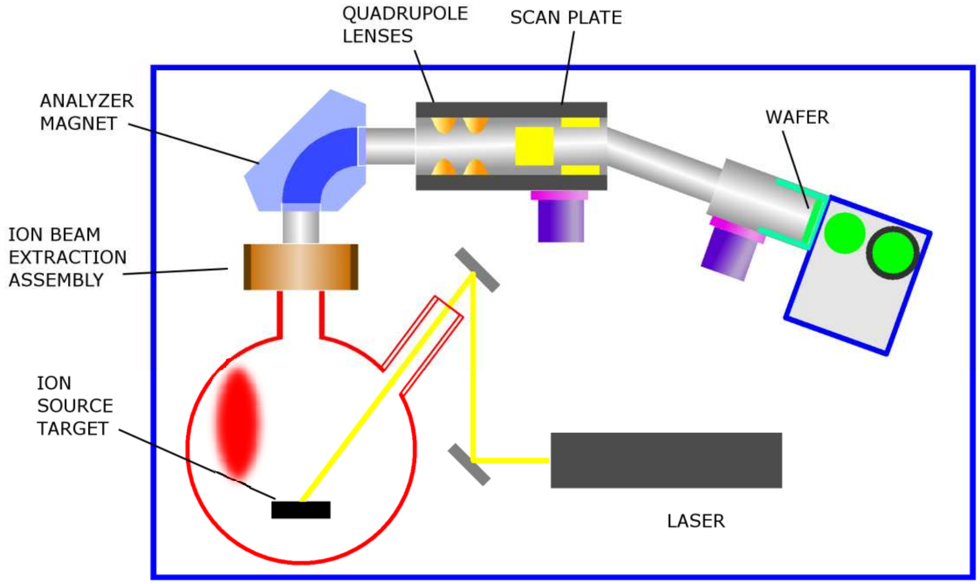
Very high current beams can be supplied easily.

This scheme could be applied to ion implantation system.

Measured charge states of Ge ions using a table top Nd-glass laser system (3J 30ns)

Unanticipated new direction related to energy efficiency driven technology developed for needs of basic research

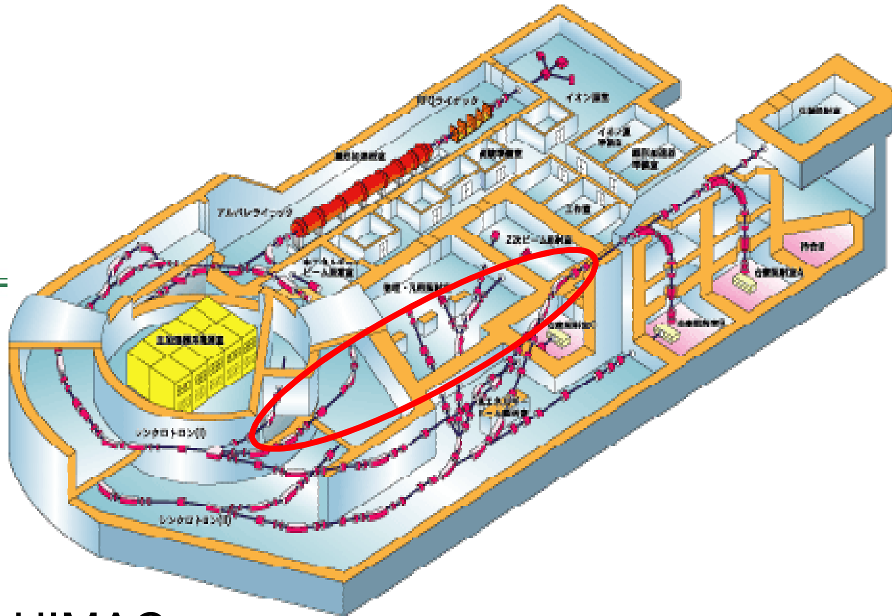
High current stable pulsed beams of Ga, B, Ge, Si can be produced for semiconductor production with the laser ion source. By using multiply-charged ions rather than singly charged ions, one can reach proportionally higher energies with the same acceleration voltage, resulting in a cheaper and more compact system.



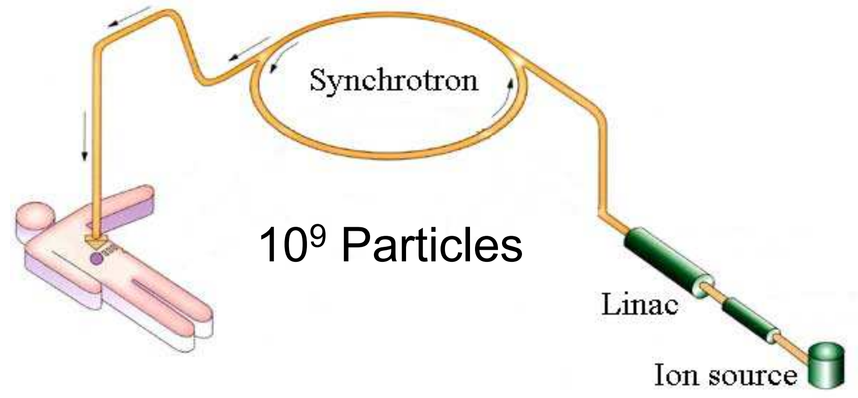
Concept for an ion implantation system using long pulse laser ion source

Insulated gate bipolar transistors (IGBT's) are used to efficiently convert power between the batteries and the motor/generator in hybrid vehicles. There is activity to improve technologies for producing IGBT's since there is a need for devices with higher reliability and higher performance. This technology is being explored at BNL; benefits include ease of reaching higher energies, avoiding the need for gases in the system, and ability to obtain the desired dose in a single laser pulse .

Fully stripped carbon beam delivery for a cancer therapy facility



HIMAC
(Heavy Ion Medical Accelerator in Chiba Japan)



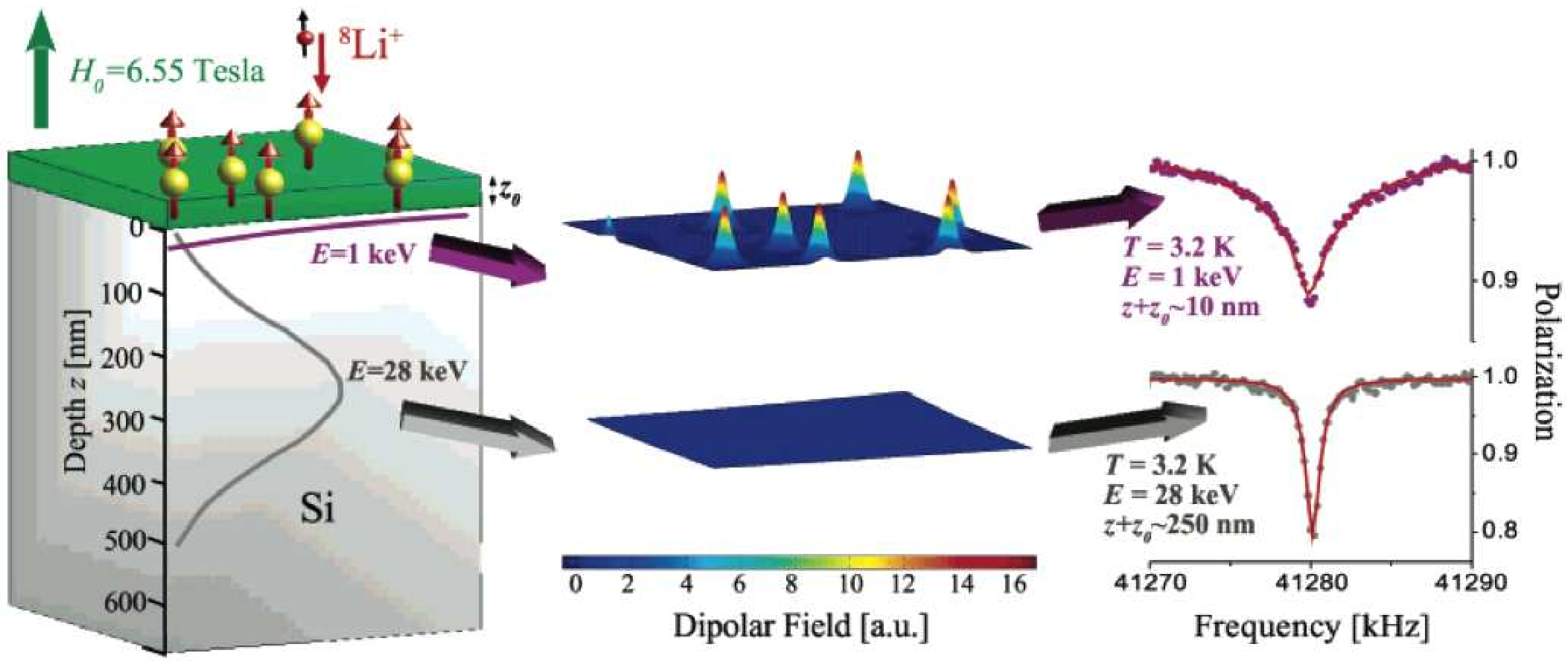
Present schemes for carbon ion therapy use a lower current, lower charge state ion source, injecting into an RFQ and linear accelerator, followed by multi-turn injection into a synchrotron.

With the laser ion source, one can produce a very high intensity carbon 6+ beam. Direct plasma injection then allows this intense beam to be captured into an RFQ accelerator. With the higher charge state, one can eliminate the linear accelerator and inject directly into the synchrotron With the high beam current, a simple single-turn injection scheme can be used. The result is that this proposed new scheme based on direct plasma injection would be cheaper, simpler, and more compact.

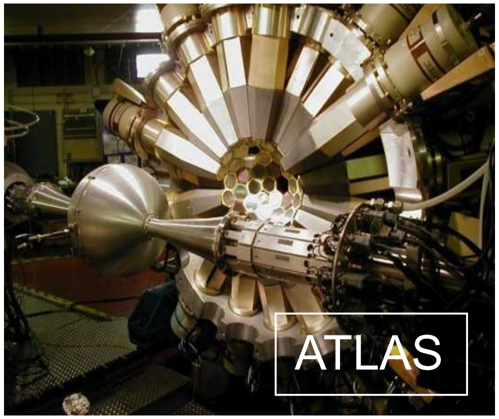
^{8}Li β-NMR Resonance Studies

- **Polarized ^{8}Li implanted below monolayer of Mn_{12} single molecule magnets on Si substrate to study dipolar field of SMM; potential application information storage, quantum research on single spins, quantum tunneling of magnetization**
- **Sensitivity 10^{13} higher than NMR**
- **Discovery potential of β -NMR very high in exploring depth dependent properties, interfaces, and proximity effects from 5 to 200 nm.**
- **Limited by availability of ^{8}Li**

Z. Salman *et al.* Nano Lett. 7 (2007) 1551

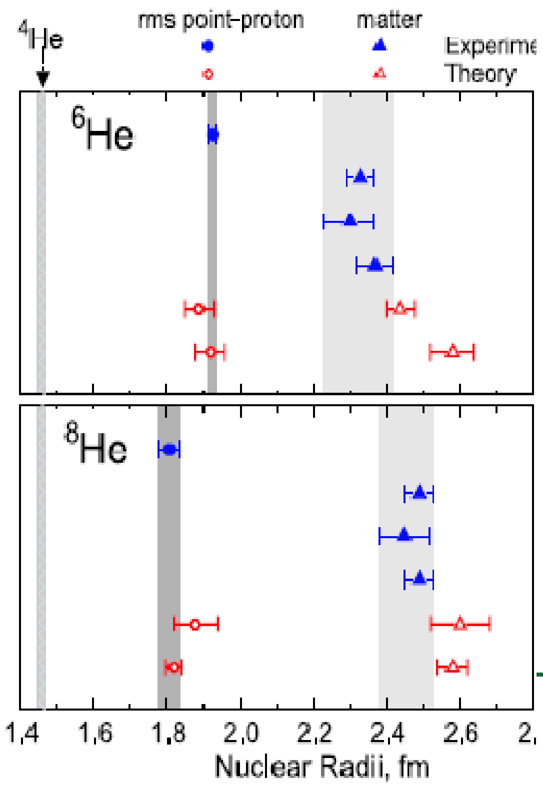


Synergy Between Basic Research and Applications of Nuclear S&T



Argonne Tandem Linac Accelerator System

Testing ab initio calculations (like those which were recognized by the Bonner Prize) of nuclear radii with atom trapping



Analyzing effects of neutron irradiation on actinides formed in nuclear fuel

New Idaho National Lab -ATLAS collab tackles nuclear fuel recycling science

- Because of the requirements of the basic research program, ATLAS can measure abundances as low as10^6 atoms
- Less irradiation is required (one 20 day ATR cycle)
- Much faster turn-around than chemical seperation
- Much greater precision is achieved

Capabilities developed because of requirements of Basic research serving national need

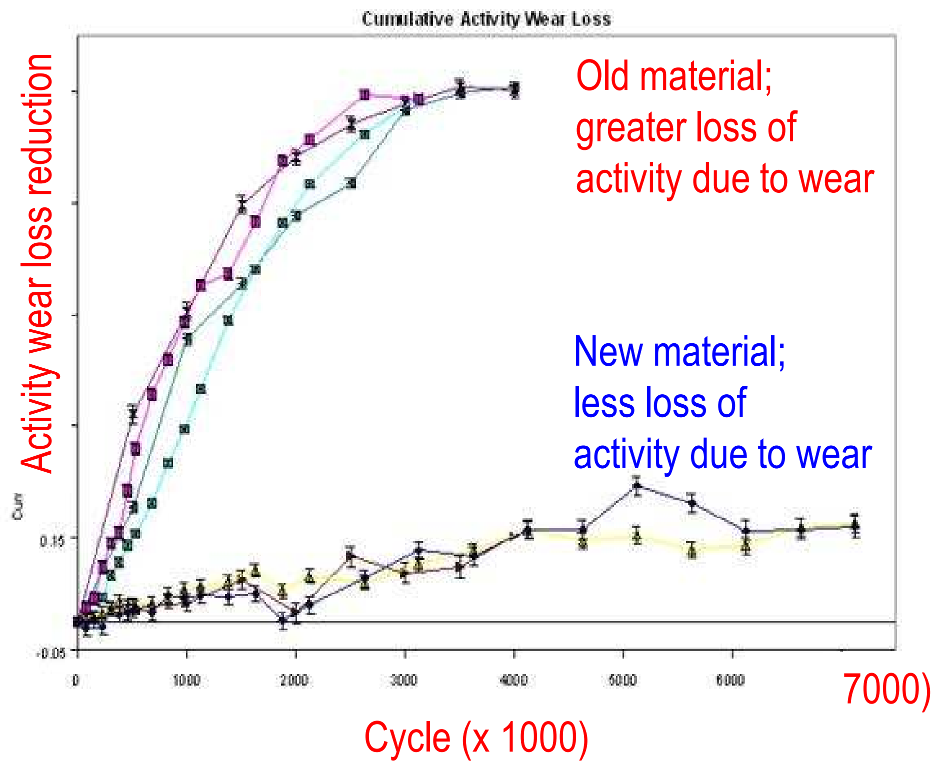
Statement of Problem: Effective means of determining wear at metal-plastic pin interface (200,000 hip-joint procedures per year)

Approach:
^{7}Be produced in Atomki (Hungary) via 7Li(p,n)7Be reaction chemically separated at Holifield Rare Isotope Beam Facilit & uniformly implanted to 9 µm in test material using setup from Colorado School of Mines to give activity plateau

Motion wear simulator from Rush University Medical Center Chicago deployed at Argonne National Laboratory

Reduction in activity of 7Be measured as a function of simulated wear cycles using a 20% Ge detector to determine wear loss. 1,000,000 cycles possible in a week; well matched to half life of ^{7}Be

Preliminary Indication of this proof of principle test: New material approximately 13 times more resistant to wear than material used previous material



Cumulative 7Be activity wear loss versus wear cycles.

Upper group of curves: standard high density polyethylene;

Lower group of curves: new cross-linked high density polyethylene

New material is about 13 times more resilient to wear.

Challenges

One challenge is effectively carryout the planned basic research program

An even greater challenge, because the connections are not always obvious or immediate, is to articulate how basic research is an effective engine which can, does, and will deliver solutions that help the nation meet challenges in energy, materials, sustainability, and more near and long term

The nuclear science community has a voice which is unique in its insightfulness near and long term, and which is highly respected

In addition to delivering discovery science, it is very important for the nuclear science community to help articulate this message

Final Comment

The future…

Is in your hands

What has sustained the field and served it well…

Delivering value in terms of discovery science, new knowledge, new technology, important applications

The challenge is yours to make the future a good one

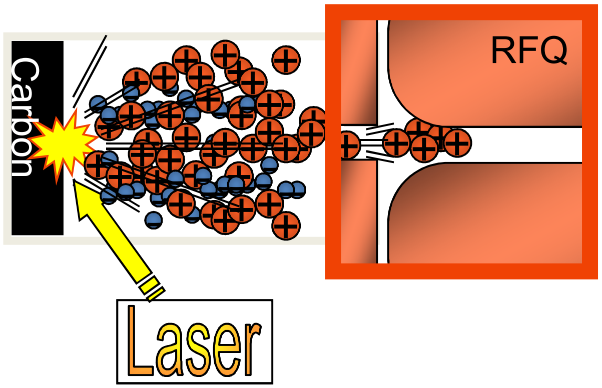
Additional Detail

A Similar Example

Direct Plasma Injection Scheme (DPIS) for Cancer Therapy Facility

Development of improved sources of high charge state heavy ions is important as part of a more versatile preinjector for RHIC. The Laser Ion Source with direct plasma injection into an RFQ accelerator produces beams with high charge state and very high beam current.

DPIS source



A relatively low power, commercially available laser hits a solid target containing material of the desired beam species. Material is ablated and ionized, producing a plasma containing high charge state ions. This plasma drifts to an RFQ accelerator, avoiding space charge repulsion, where a very high current of ions is then accelerated.

High density plasma from solid
100 mA
Extremely compact
Charge state : 6+
Only small laser
Simple structure

In addition to this application as part of a heavy ion preinjector, this technology could be used to reduce the cost and complexity of accelerators built for cancer therapy.